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13. ABSTRACT *(Maximum 200 Words)*

An experimentally validated thermomechanical actuation model for shape memory alloy (SMA) actuators undergoing non-proportional cyclic loading, fully coupled with the evolution of plastic strains is developed. The model is numerically implemented in a form suitable for finite element analysis. Material characterization of SMA actuators is also performed in this research effort. Emphasis is given on the effect of plastic strains on the properties of SMA actuators. The data collected during the characterization is utilized to calibrate the thermomechanical SMA model. After the model is calibrated, different loading cases are investigated, including non-proportional loading paths. Finally, the fatigue life of SMA actuators is also investigated. A test frame for fatigue experiments is developed and numerous fatigue tests are performed.

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Thermomechanical Modeling and Experimentation for SMA Actuators under Cyclic Loading

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Final Report

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1 Objectives

The objectives of this research effort are to develop an experimentally validated thermomechanical actuation model for shape memory alloy (SMA) actuators undergoing non-proportional cyclic loading, fully coupled with the evolution of plastic strains. Complete integration of the thermomechanical SMA model in the design process requires the ability to identify model parameters for any SMA chosen for implementation into a structure, thus becoming an objective of this research. Additionally, a goal of this research is to extend the knowledge level for cyclic loading of SMAs to large numbers of cycles to determine the thermal cyclic fatigue life of SMAs. Finally, Finite Element Analysis (FEA) of smart structures with SMA actuators will be performed, emphasizing analysis of coupling mechanisms

2 Basic Research Issues

The basic research issues of the research include the following three major aspects:

1. Modeling of 3-D thermomechanical constitutive response of SMAs undergoing stress-induced phase transformation;
2. Development of numerical tools for the implementation of 1-D and 3-D thermomechanical response of SMA for use in actuator analysis;
3. Determination of the thermal cyclic fatigue limit of SMAs under simple loading paths and characterize the influence of the material condition on fatigue limit.

3 Significant Results

3.1 Constitutive Modeling of SMAs

A thermomechanical description of the martensitic phase transformation and the associated shape memory effect in polycrystalline SMAs has been completed [4, 6, 10]. The rate-independent constitutive relations are derived in the stress-temperature space using a Lagrangian formulation. The Kuhn–Tucker optimality conditions, constraints on evolution equations for transformations strain and shape of transformation function in thermodynamic force space are obtained naturally through the principle of maximum transformation dissipation. Various transformation functions (J_2 type, J_2–I_1 type and J_2–J_3 type) are investigated and a generalized (J_2–J_3–I_1 type) transformation function is proposed, where J_2, J_3 and I_1 are the second deviatoric stress invariant, third deviatoric stress invariant and the first stress invariant, respectively. Results of the model based on different transformation functions are compared with experimental results to determine their accuracy to predict SMA characteristics like

tensioncompression asymmetry, negative volumetric transformation strain and pressure dependence. It is concluded that J_2–I_1 type transformation function is more effective in capturing 3-D stress induced phase transformation [10].

3.2 Numerical Implementation of SMA Constitutive Models

The analysis of the structure of equations representing SMA constitutive behavior has shown that they can be very similar to those of rate-independent plasticity models. Such a structure allows techniques used in rate-independent elastoplastic behavior to be directly applicable to SMAs. A comprehensive study [9] on the numerical implementation of SMA thermomechanical constitutive response using return mapping (elastic predictor-transformation corrector) algorithms is presented.

The closest point projection return mapping algorithm which is an implicit scheme is given special attention together with the convex cutting plane return mapping algorithm, which is an explicit scheme. The closest point algorithm involves relatively large number of tensorial operations than the cutting plane algorithm besides the evaluation of the gradient of the transformation tensor in the flow rule and the inversion of the algorithmic tangent tensor. Remarks on numerical accuracy of both algorithms are given, and it is concluded that both algorithms are applicable for this class of SMA constitutive models and preference can only be given based on the computational cost [9].

3.3 Material Characterization of SMA Actuators

The focus of this research task is the thermomechanical characterization of SMA quantifying the effect of plastic strain on the transformation characteristics of SMA actuators. The thermomechanical response and transformation characteristics of a NiTiCu and a NiTi SMA wires have been studied [7] as a function of the induced plastic strain for four different loading paths: (i) an elastic–plastic loading of the austenitic phase; (ii) a stress–induced martensitic phase transformation; (iii) an elastic–detwinning–plastic loading of the martensitic phase; and (iv) a thermally-induced phase transformation under a constant applied stress.

Each loading path is repeated multiple times, with an incremental change of the total applied strain, to determine the effect of accumulated plastic strain on the phase transformation characteristics of the two SMA material systems. The effects of plastic strain have been quantified by measurements of recoverable strain during a thermal cycle under zero applied stress, measurements of heat of transformation from a differential scanning calorimeter and microstructural evaluations [7].

The influence of cold work and heat treatment on the shape memory effect and plastic strain development has also been investigated for the thermally induced phase transformation of NiTi SMA wires under constant applied stress [8]. Fully annealed SMA wire specimens of identical chemical composition have been cold rolled to reduce the specimen width 10, 20, 30 and 40% of the initial wire

diameter and then annealed at 300°C, 400°C or 500°C for 15 min. Thermally induced phase transformations under constant applied stress, at various levels up to 500 MPa, have been performed to identify the effect of the cold work percentage and annealing temperature on the development of transformation and plastic strain in SMA specimens with one-way shape memory.

Results [8] show the maximum transformation strain is independent of cold work percentage and annealing temperature, and increased cold work, for similar annealing temperatures, raises the stress level for the onset of plastic strain and decreases the additional plastic strain development. Also, a reduction in annealing temperature, for similar cold work percentage, raises the stress level for the onset of plastic strain and decreases the additional development of plastic strain. In addition to the one-way SMAs described above, specimens with similar heat treatments are trained with two-way shape memory under a constant applied stress of 300 MPa. Increased cold work percentage is shown to reduce the plastic strain accumulation during the two-way training, as well as the amount of two-way strain developed in the specimens. A comparison between the untrained and trained specimens of identical cold work and annealing temperature shows a reduction in the maximum transformation strain.

3.4 SMA Actuators Undergoing Nonproportional Loading

The constitutive response of SMA wire actuators under thermomechanical nonproportional loading has been investigated in a series of experiments [3, 2]. During the experiments the behavior of NiTi SMA wires loaded by an elastic spring and undergoing thermally-induced phase transformation has been observed. The experimental results have been utilized to estimate the material parameters for the NiTi SMA. Using the estimated parameters, the response of the SMA actuators has been predicted using a constitutive model developed in an earlier work [1]. Model predictions have been compared with the experimental results.

3.5 Fatigue of SMAs

The focus of this research task is to determine the thermomechanical fatigue life of an SMA under cyclic loading which involves phase transformation. To accomplish this task, a novel test frame for testing SMA wires undergoing thermally-induced phase transformation has been designed and built [5]. A testing protocol necessary to fully establish the fatigue characteristics of SMAs under various conditions has been developed. Results for the fatigue life of NiTiCu (K-Alloy) undergoing thermally-induced phase transformation under constant applied stress have been obtained [5]. The results indicate a significant increase in the number of cycles to failure as the applied stress level is approximately equal to 100 MPa while a sharp decrease in the fatigue life is observed for stress levels greater than 100 MPa.

4 Personnel Supported

Faculty:	D.C. Lagoudas
Post-Docs:	Z. Bo
Graduate Students:	M. A. Qidwai
	D. A. Miller
	E. L. Vandygriff
	P. A. Popov
	C. C. Li
	J. J. Mayes
Undergraduate Students:	A. Wright
	R. M. Layer
	C. Schwarzbach
	J. F. Renaud

5 Interactions and Transitions

5.1 Participation, Presentations at Meetings, Conferences, Seminars, etc.

Invited Lectures

"Modeling of Cycling Thermomechanical Response of SMA's," The Department of Mathematical Sciences, The University of Nevada, Las Vegas NV.

"Numerical Implementation of a Thermomechanical Constitutive Model for Shape Memory Alloys using Return Mapping Algorithms," NATO Advanced Workshop on Shape Memory Alloys: Bridging the Scales from Micromechanics to Structural Applications - University of Metz, Metz, France, May 14, 1998.

"Modeling and Experiments of the Hysteretic Response of an Active Hydrofoil Actuated by SMA Line Actuators," SMART-98, Pultusk, Poland, June 16-19, 1998.

"Constitutive Relations for Shape Memory Alloys," 3rd National Congress on Computational Mechanics, Volos, Greece, June 24-26, 1998.

"Modeling of SMAs and their Applications in Smart Structures," University of Hannover, Germany, May 22, 1998.

Conference Presentations

"Thermomechanical Modeling of Cyclic Response of Shape Memory Alloys with Minor Hysteresis Loops," International Seminar entitled Actual Problems of Strength, St. Petersburg State University, St. Petersburg, Russia, October 12-22, 1997.

"Thermomechanical Coupling in SMA Actuators," 1997 ASME IMECE Meeting, Wyndham Anatole, Dallas, TX, November 17-21, 1997.

"Thermomechanical Modeling of Shape Memory Alloys Undergoing Cycling," 1997 ASME IMECE Meeting, Wyndham Anatole, Dallas, TX, November 17-21,

1997.

"FEM Implementation of a Thermomechanically Coupled Finite Deformation SMA Constitutive Model," SPIE's 5th Annual International Symposium on Smart Structures and Materials," Catamaran Resort Hotel, San Diego, CA, March 1-5, 1998.

5.2 Consultative and Advisory Functions to Other Laboratories and Agencies

- Consultant to the DOD as a member of the Defense Science Study Group, comprised of fifteen scientists and engineers, distinguished in their technical fields.
- Advisor on SMA constitutive modeling and numerical implementation to NRL, Northrop Grumman, Boeing, and MIT Lincoln Labs.

5.3 Transitions

SMA material subroutine (Software):

- V. G. DeGiorgi, Mechanics and Materials Branch, Naval Research Laboratory.
- Ed White and Jim Dunne, Smart Structures and Systems Group, Boeing, Phantom Works.

6 Honors and Awards

- Associate Editor, Journal of Intelligent Materials Systems and Structures and Journal of Smart Materials and Structures
- TEES Senior Research Fellow
- TEES Faculty Fellow
- Board of Directors (Treasurer), Society of Engineering Science
- IDA - Defense Science Study Group, Member
- ASME Elasticity Committee, Vice Chair

Publications

[1] Z. Bo and D. C. Lagoudas. Thermomechanical modeling of polycrystalline SMAs under cyclic loading, Parts I–IV. *Int. J. Eng. Sci.*, 37:1089–1204, 1999.

[2] Z. Bo, D. C. Lagoudas, and D. Miller. Material characterization of SMA actuators under nonproportional thermomechanical loading. *Journal of Engineering Materials and Technology*, 121:75–85, 1999.

[3] Z. Bo, D. C. Lgoudas, and D. Miller. Behavior of SMA actuators under non-proportional thermomechanical loading. In *Proceedings of SPIE Conference*, 1998.

[4] D. C. Lagoudas, Z. Bo, J. G. Boyd, and M. A. Qidwai. Thermomechanical modeling of shape memory alloys and composites. In A. Guran, H. S. Tzou, G. L. Anderson, and M. C. Natori, editors, *Structronic Systems: Smart Structures, Devices and Systems*, volume 4 of *Series B*, pages 197–246. World Science Publishing Company, 1997.

[5] D. C. Lagoudas and D. A. Miller. Experiments of thermomechanical fatigue of SMAs. In *Proceedings of SPIE Conference on Smart Materials and Technologies*, volume 3675, Newport Beach, CA, March 1999.

[6] D. C. Lagoudas and M. A. Qidwai. Constitutive modeling of 3-D stress induced phase transformation in polycrystalline NiTi SMA. In *Proceedings of IMECE'99*, Nashville, TN, November 14–19 1999. ASME.

[7] D. A. Miller and D. C. Lagoudas. Influence of cold work and heat on the shape memory effect and plastic strain development of NiTi wire actuators. *Material Science and Engineering A*, 308(1–2):161–175, 2001.

[8] D. A. Miller and D. C. Lagoudas. Influence of cold work and heat treatment on shape memory effect and plastic strain development of NiTi. *Material Science and Engineering A*, 308:161–175, 2001.

[9] M. A. Qidwai and D. C. Lagoudas. Numerical implementation of a shape memory alloy thermomechanical constitutive model using return mapping algorithms. *Int. J. Numer. Meth. Eng.*, 47:1123–1168, 2000.

[10] M. A. Qidwai and D. C. Lagoudas. On thermomechanics and transformation surfaces of polycrystalline NiTi shape memory alloy material. *Int. J. Plasticity*, 16:1309–1343, 2000.